

Comments on “Asking Photons Where They Have Been ”

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By using the nonuniform discrete Fourier transform on the center positions of the symmetric intensity distribution of the output beam, we recover the vibration information of two mirrors, which is lost in the analysis of Danan *et al.* in the work [Phys. Rev. Lett. **111**, 240402 (2013)]. We believe a photon always follows continuous trajectories, and a photon has to enter an interferometer at first and then leave it, if this photon has ever been inside the interferometer.

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Recently, a very interesting experiment was reported in a modified Mach-Zehnder interferometer system [1]. The authors encoded the photon's path information by slightly vibrating five mirrors inside the interferometer at different frequencies, and finally deduce the photons' trajectory through the power spectrum of the output beam. An interesting phenomenon is found in the second experiment of the work [1], where the power spectrum records the vibration of the mirrors A , B and C , but without the vibration information of the other two mirrors E and F . They thus claimed that “the past of the photons is not represented by continuous trajectories”, and some photons “have been inside the nested interferometer, but they never entered and never left the nested interferometer” [1].

We have to say that such an interpretation is challenging our intuition too. A basic fact is that the probabilities of finding photons in the beams A and B in principle sum up to the probability of finding photons in the beam E (or F) all the time. Secondly, our numerical simulation shows that the peaks of f_A and f_B in the second spectrum in Fig. 2 of the reference [1] reduce with the increase of the vibration amplitude of the mirror E or F (and disappear finally), accompanied by the appearance of some “noisy” peaks, which is an evidence that the vibration of the mirrors E and F plays a role in the evolution and spatial distribution of the output beam.

We believe the output beam D indeed carries the vibration information of the two mirrors E and F , which can be recovered through the following method. First of all, we use a charge-coupled device (CCD) to replace the quad-cell photodetector to record the real-time intensity distribution of the output beam. It is not hard to infer from Eq. (4) in the reference [1] that the intensity has an asymmetric vertical distribution at most time. However, once the intensity distribution become symmetric in the vertical direction, we record its center positions and finally Fourier transform the recorded data.

From the Eq. (4) in the reference [1], we know that the symmetric intensity distribution occurs when anyone of the following three conditions is satisfied, (i) $\delta_A = \delta_B$; (ii) $\delta_C = \delta_B + \delta_E + \delta_F$; (iii) $\delta_A + \delta_C = 2\delta_B + \delta_E + \delta_F$. As a nonlinear function of time t , each one of the three equations has a series of nonuniform roots. That is to say, the data we sampled in the discrete Fourier transform of the center positions of symmetric intensity distribution (CPSID) are neither uniform nor completely random. We can randomly pick out a part of CPSID data to make the nonuniform discrete Fourier transform (NUDFT) [2] and need not take into account all records of CPSID.

In our simulation, we randomly choose $N = 2.4k$ points among about $108k$ effective CPSID within 60 seconds. The

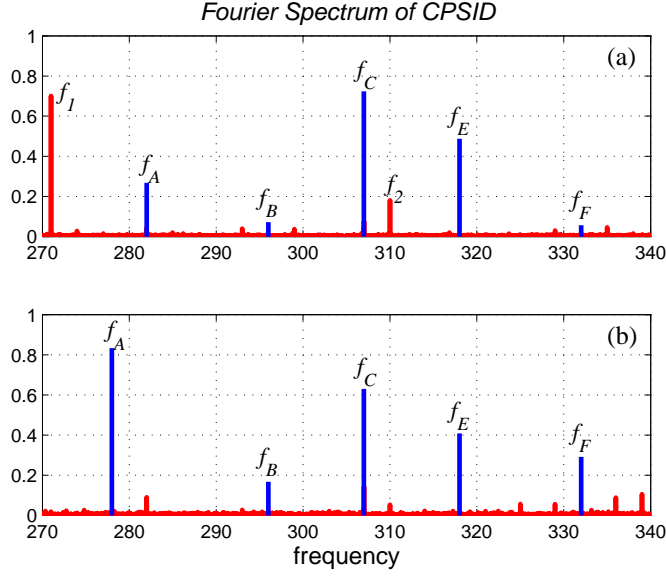


FIG. 1: (Color online). (a) The vibration frequency of each mirror, f_i ($i = A, B, C, E, F$), has a peak in the Fourier spectrum of the CPSID. (b) The peak of f_F is enhanced substantially by slightly changing the frequency f_A from 282Hz to 278Hz.

Fourier spectrum of these CPSID data is plotted in Fig. 1 in the range [270Hz, 340Hz]. For simplicity, each involved frequency is set identical to the one used in the reference [1]. Here we see that all these five frequencies appear in the Fourier spectrum of the CPSID, accompanied by a few “noisy” peaks. In fact the CPSID data collected in the current way can be considered as the discrete points of a continuous function,

$$y(t) = \delta_A - \delta_B + \delta_C + p(\delta_A - \delta_B)(\delta_B - \delta_C + \delta_E + \delta_F)(\delta_A - 2\delta_B + \delta_C - \delta_E - \delta_F), \quad (1)$$

with p a constant. The peaks in the Fourier spectrum of this continuous function are located at the same frequencies as those we derived from the CPSID data and plotted in Fig. 1(a), but with different magnitudes and shapes, which helps to explain the existence of other frequencies besides the five ones we concern, see Fig. 1(a). Each “noisy” peak can be expressed as a linear combination of the five frequencies in a simple way, e.g. $f_1 = 271\text{Hz} = f_A + f_C - f_E$ and $f_2 = 310\text{Hz} = f_B - f_E + f_F$. The low peak of f_F in Fig. 1(a) is related to the coincidence, $f_F = f_B + f_E - f_A$. By slightly modifying the frequency f_A from 282Hz to 278Hz, we can achieve two strong peaks for f_E and f_F , see Fig. 1(b). Although the strict requirements on the high spatial resolution, fast response and high precision for the CCD might bring some obstacles for practically implementing the measurement introduced here, the physics revealed by it theoretically can not be denied. The photons ever inside the nested interferometer must have entered and left the nested interferometer. A photon always follows continuous trajectories.

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[2] L. Greengard and J. Lee, SIAM Review **46**(3), 443-454 (2004).